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EXPERIMENTAL INVESTIGATION OF THE LASER-DRILLED HOLES IN ALUMINIUM

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Lucrarea prezintă un studiu experimental al găuririi în aer a unei plăci de aluminiu folosind pulsuri laser scurte cu lungimea de undă de 532 nm. A fost analizată morfologia suprafeţei plăcii în jurul craterelor şi rata de ablaţie în funcţie de fluenţa laser. Rezultatele obţinute indică o creştere exponenţială a ratei de ablaţie cu fluenţa (până la ~20 nm/puls) în apropierea pragului de ablaţie, urmată de o creştere logaritmică (până la ~200 nm/puls) când fluenţa este mai mare decât 100 J/cm^2. Morfologia suprafeţei din jurul craterelor este determinată în funcţie de fluenţa laser prin măsurarea diametrului zonei afectate termic şi a înălţimii depunerii. La fluenţe apropiate de cea de prag, diametrul craterului este de ~10 μm şi nu se observă o regiune afectată termic sau depuneri importante în jurul craterelor. Creşterea fluenţei conduce la creşterea zonei afectate termic şi a înălţimii depunerii în jurul craterelor, indicând o favorizare a ejecţiei de material topit sub acţiunea presiunii de recul a plasmei.

We investigate experimentally the aluminium drilling by using multiple nanosecond laser pulses at 532nm wavelength in open air. We analyzed the surface morphology around the craters and the ablation rate as a function of laser fluence. The results indicate that the ablation rate of aluminium increases exponentially with fluence to ~20 nm/pulse near the ablation threshold, and logarithmically to ~200 nm/pulse when the fluence is >100 J/cm^2. We assessed the surface morphology around the craters as a function of fluence by measuring the diameter of the heat-affected zone and the height of the crater's rim. At fluences near the threshold, the crater diameter is ~10 microns and there is no significant heat-affected zone and rims around the craters. Increasing fluence leads to the increment of the heat-affected zone and the rim's height, indicating an enhanced melt ejection under the recoil pressure of the plume.

Keywords: Ablation rate, fluence, ablation threshold fluence.

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1. Introduction

The efficiency of material removal from a material subjected to intense laser pulses is described by the ablation rate. The ablation rate gives the layer thickness that is removed during a laser pulse. The ablation rate is a key parameter in practical applications of laser ablation such as laser processing, pulsed lasers deposition, optoelectronics, or laser-induced plasma spectrometry [1-9]. Previous experiments on laser ablation indicated that the ablation rate depends strongly on the laser beam's characteristics, e.g. laser fluence, beam diameter, wavelength, pulse duration, pulse repetition frequency [1-4, 6, 10-22]. Our previous experiments on pulsed laser ablation indicated that the ablation threshold fluence of metals is directly related to the optical absorption coefficient [11], whereas the ablation rate of the materials has a sudden jump when increasing the fluence above a threshold value by changing the beam diameter. This threshold was demonstrated to be directly related to the plasma hydrodynamic length which became of the same order of magnitude with beam diameter at the threshold. We demonstrated theoretically, by using a 1D photo-thermal model which involves numerical solve of the heat equation with large beams as heat source, that the ablation results from the superposition of two main phenomena: evaporation and melt ejection under the action of plasma recoil pressure [16].

Here, we investigate the ablation rate and the characteristics of the laser drilled craters in aluminium plates as a function of the fluence of a nanosecond laser pulses in atmospheric air at 532 nm wavelength. The experiments provide a useful insight into the phenomena of 'ablation rate jump' and 'clean' laser drilling of metals which is a stringent task for aircraft-engines cooling holes. By extrapolating to zero the fitting curves which describe the dependence of the ablation rate on fluence, we additionally estimate the ablation threshold fluence.

2. Experiments

We used in our experiment a Q-switched Nd:YAG laser system that works in the TEM00 mode and provides pulses of 4.5 ns duration at 10 Hz repetition rate and 1064 nm wavelength. The second harmonic at 532 nm is obtained by using the second harmonic generator modules. The pulse energy is varied in the range of ~10 µJ to ~6 mJ by using a variable attenuator, whereas a beam-expander is used for expanding the beam from 3mm to about 3 cm diameter. The laser pulses are focused at normal incidence by a focusing lens (f/6, f=18 cm) on the surface of a thick aluminium plate (thickness larger than 1 mm). The aluminium plate is placed in the focal plane of the lens, the theoretical focused beam diameter (approximated by the central Airy disk) being of ~10 microns (Fig. 1). Thereby, the laser fluence is given by the ratio of the pulse energy and the beam area.

The craters characteristics such as diameter, depth and rims width around the craters were measured by using a metallographic microscope with micrometric resolution. Depending on how large the fluence is as compared to the ablation threshold fluence, the craters are drilled by irradiating the target with 20 to 200 pulses. Then the ablation rate is derived as the crater depth over the pulse number.

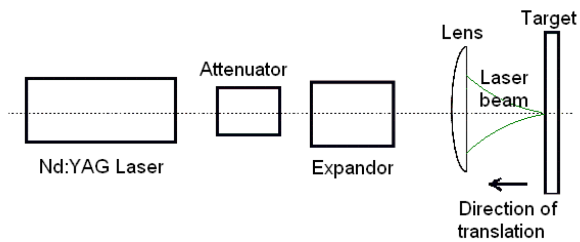


Fig. 1. Experimental set-up

We set this pulse numbers in order to get an approximate constant ablation rate during multiple pulses drilling, as indicated in [1, 15], and to obtain a crater sufficiently deep so as to obtain a small uncertainty in determining the ablation rate. By taking into account the microscope resolution and the depth of the craters, the relative error for the measured ablation rate is ~5%.

3. Results and discussion

The dependence of the craters depth (*h*) on aluminium on the laser fluence (*F*) is presented in Fig. 2. The figure indicates that the crater depth increases logarithmically with fluence up to ~80 μm when irradiating with 20 pulses. Further increase of the fluence leads to a linear increase of the crater depth up to 250 μm. For second irradiation regime (200 pulses) the crater depth increases logarithmically with fluence up to ~30 μm. The fitting curves for the logarithmic domains are described by a general equation of the form:

$$h = a \ln(F / F_0) \ (\mu\text{m}) \tag{1}$$

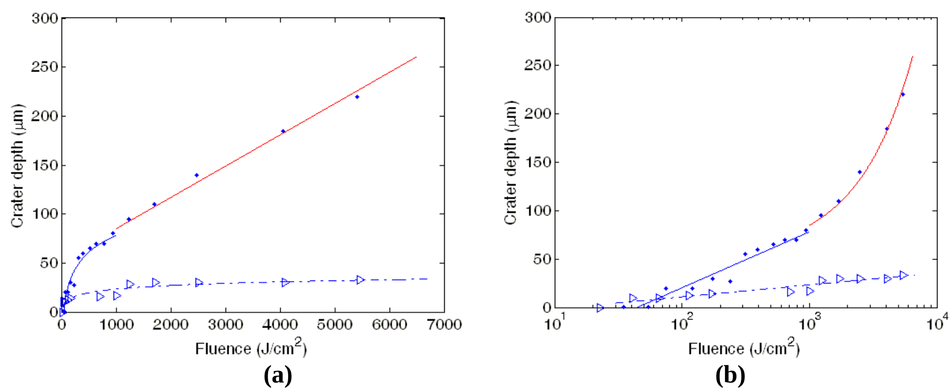


Fig. 2. Dependence of crater depth vs. laser fluence when irradiating aluminium probe with 20 pulses (points) and more than 200 pulses (triangles) at 532 nm wavelength: (a) linear axes (b) semi-logarithmic axes.

where h denotes the crater depth, a is a constant, F is the laser fluence and F_0 denotes the threshold fluence. Thus, for 20 pulses irradiation regime the fitting curve is:

$$h = 25\ln(F/25) \quad (\mu\text{m}) \tag{2}$$

whereas for more than 200 pulses irradiation regime the fitting curve is:

$$h = 5.4\ln(F/10) \quad (\mu\text{m}) \tag{3}$$

Equations (2) and (3) indicate that the ablation is more efficient in the case of the 20 pulses irradiation regime, the ablation rate at the highest fluence (~5400 J/cm^2) being ~11 μm/pulse in the first regime, and ~0.2 μm/pulse in the second regime. Moreover, the ablation threshold fluence is smaller when the target is irradiated with 200 pulses (~10 J/cm^2), comparatively with 20 pulses regime (~25 J/cm^2).

The decrease of the ablation rate with the pulse number for a constant fluence can be related to the confinement of the ablated plasma-plume within the crater. During a laser pulse the ablated species travel away from the target around ~20÷200 μm [1]. This means that the hydrodynamic length of the plasma plume is comparable with the ablated depth and a strong attenuation of the laser beam by scattering and inverse Bremsstrahlung absorption into the confined plasma plume take place. Moreover, the trapping of the plasma favours the recondensation of the material due to the less efficient transport of the ablated species out of the crater.

Analysing the curve described by the equation (2) in Fig. 2, we observe that the logarithmic dependence of the crater depth on fluence holds only for fluences up to ~1000 J/cm^2 and change to a linear dependence for higher fluences.

This effect originates in the superposition of the following two phenomena: the phase explosion and the change in the plasma plume hydrodynamics. The phase explosion phenomena appear when the target surface temperature reaches the thermodynamic critical temperature [19, 23], and a transition from a normal vaporization to phase explosion regime take place that enhances the ejection and re-deposition of droplets around the craters. Thus, when fluence is smaller than ~300 J/cm^2 the ablated craters analysed on microscope present a good aspect ratio, the quantity of re-deposited material around and inside the crater is small (~1 μm).

The change in the hydrodynamics of plasma plume from one-dimensional to three-dimensional expansion regime implies changes in the laser-plasma interaction. The first regime is characterised by a high density and axial expansion whereas the second regime is defined by a low density and both axial and radial expansion [3].

The effect of laser fluence on ablated crater diameter is depicted in Fig. 3. The fitting curves are described by a general equation of the form:

$$d = b\ln(F / F_0) \ (\mu\text{m}) \tag{4}$$

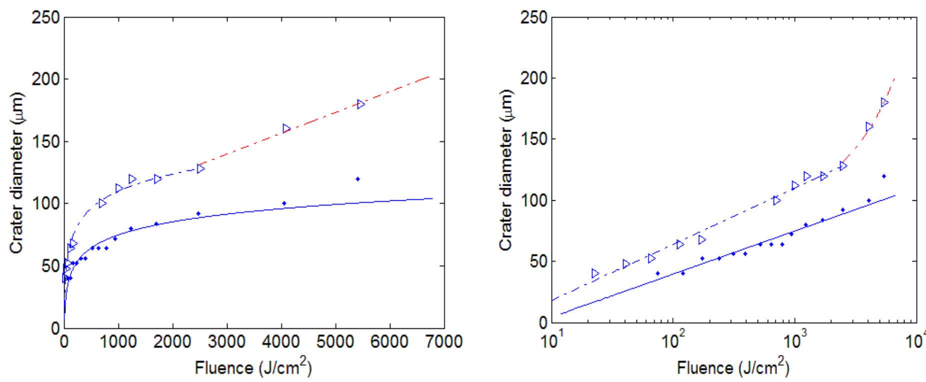
where d denotes the crater diameter and b is a constant. For 20 pulses irradiation regime the fitting curve is:

$$d = 17\ln(F/25) \quad (\mu\text{m}) \tag{5}$$

whereas for more than 200 pulses irradiation regime the fitting curve is:

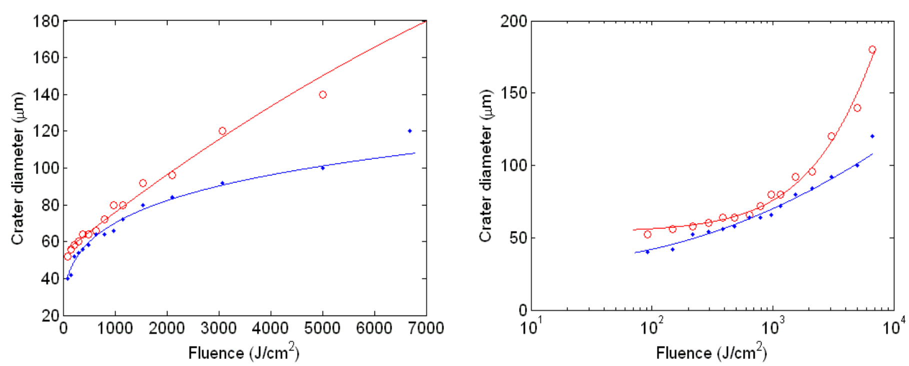
$$d = 20\ln(F/10) \quad (\mu\text{m}) \tag{6}$$

Fig. 3 indicates a logarithmic increase of the crater diameter with fluence (when using 200 pulses) only for fluences <2500 J/cm^2, and an approximately linear increase above this value. The crater diameter at this fluence is ~80 μm for first irradiation regime, and ~130 μm in the case of second regime. The higher values of the crater diameter in the second regime are determined by the plasma confinement inside of the craters that leads to a strong attenuation of the incident laser by inverse Bremsstrahlung. This implies a strong heating of the plasma plume which changes its hydrodynamic expansion from one-dimensional to three-dimensional, and an increase of the thermal affected area.



(a) (b)

Fig. 3. The influence of laser fluence on ablated crater diameter when irradiating aluminium probe with 20 pulses (points) and more than 200 pulses (triangles) at 532 nm wavelength: (a) linear axes (b) semi-logarithmic axes.



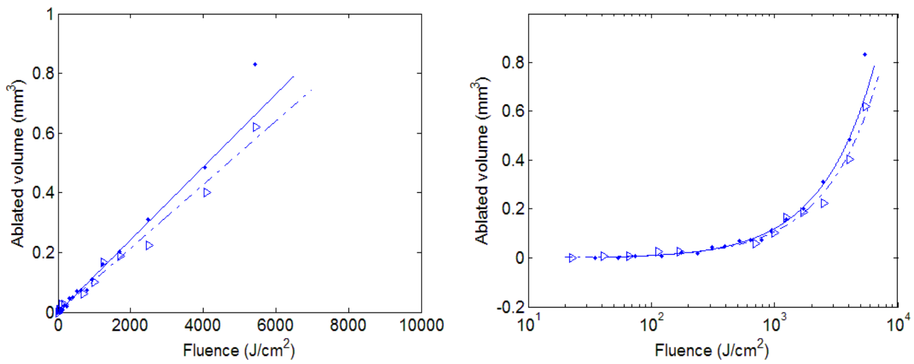
(a) (b)

Fig. 4. The influence of laser fluence on ablated crater diameter (points) and thermal crater diameter (circles) when irradiating aluminium probe with 20 pulses at 532 nm wavelength: (a) linear axes (b) semi-logarithmic axes.

Fig. 4 presents the dependence of the ablated crater diameter (points) and the thermal crater diameter (circles) on laser fluence when aluminium target is irradiated with 20 pulses. An approximately logarithmic increase of both ablated crater and thermal crater diameter is observed up to ~80 μm when fluence increases around ~2000 J/cm^2. At this value of laser fluence a step increase of thermal crater is observed. This can be explained as follows: for an usual plasma temperature of ~50000 K the hydrodynamic length of plasma

$$l_h = v_T \tau_p \tag{7}$$

is ~80 μm which is similar to the crater diameter and crater depth. In equation (7), $v_T = (\gamma\, k_B T_p / M)^{1/2}$ is the expansion velocity of the plasma plume considered as an ideal gas with adiabatic coefficient $\gamma = 5/3$, temperature T_p and the atomic mass M, k_B is the Boltzmann constant, and τ_p is the pulse duration.



(a) **(b)**

Fig. 5. The influence of laser fluence on ablated crater volume when irradiating aluminium target with 20 pulses (points) and more than 200 pulses (triangles) at 532 nm wavelength: (a) linear axes (b) semi-logarithmic axes.

The effect of laser fluence on ablated material volume is depicted in Fig. 5. By analysing on the microscope the shape of the ablated crater we estimate that the crater can be approximated with a cone for both irradiation regimes. The data presented in Fig.5 indicate a linear increase of the ablated volume with laser fluence and a very small difference between the craters volumes drilled with 20 and 200 pulses. For example, the ablated volume at 4 kJ/cm^2 fluence is ~0.4 mm^3 and ~0.45 mm^3 in the case of 200 and 20 pulses irradiation regimes, respectively. The approximate equality of the two ablated volumes indicates that increasing the pulse number at a certain fluence leads to larger and shallower craters while the ablated volume keeps constant.

4. Conclusion

Here, we investigated experimentally the laser drilled holes in aluminium thick plates, in air, using pulses of 4.5 ns at 532 nm wavelength in two irradiation regimes: 20 pulses and 200 pulses. We analyzed the surface morphology around the craters and the characteristics of ablated structures (crater depth, crater diameter and crater volume) as a function of laser fluence. The results indicate that the ablation threshold fluence is bigger when the target is irradiated with 20 pulses regime (~25 J/cm^2) as compared to 200 pulses regime (~10 J/cm^2). The ablation rate is demonstrated to increase approximately logarithmically with fluence and to be pulse-number dependent, being ~11 μm/pulse when using 20 pulses and decreasing to ~0.2 μm/pulse when using 200 pulses at 5400 J/cm^2 fluence. The crater diameter increases approximately logarithmically with fluence and is pulse-number dependent, being ~80 μm when irradiating with 20 pulses and ~130 μm when irradiating with 200 pulses at 2500 J/cm^2 fluence. For 20 pulses regime, when crater diameter is ~80 μm which approximately equates the plasma hydrodynamic length, a steep increase of the thermal diameter around the craters was observed. Finally, we demonstrated that the ablated volume increases linearly with fluence, obtaining approximately the same ablated volume (0.4 mm^3) in the two irradiation regimes while the craters become larger and shallower with increasing pulse number.

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